DISCUSSION BEFORE THE WIRELESS SECTION, 4TH JANUARY, 1933, ON THE TWO PAPERS BY MR. MEGAW (SEE PAGES 59 AND 72 RESPECTIVELY).

Prof. C. L. Fortescue: It would appear that Barkhausen's description of the mechanism by which electronic oscillations are generated has led to a certain amount of misconception. None of the existing explanations make clear the origin of the negative resistance-characteristic of a valve the grid of which is strongly positive. The author appears to accept the explanation that the oscillations are caused by the delay due to the inertia of the electrons, his view apparently being that those electrons which are accelerated by the combined electric fields when the anode is positive, arrive one half-cycle later, i.e. when the anode is negative. This action is, however, in no way similar to that of a reactive oscillator, because it is the anode—the ultimate goal of the electrons—which causes the acceleration in the early part of the cycle. Thus any additional energy the electrons may acquire in the first half-cycle is at the expense of the oscillatory circuit. Benham has partly overcome this difficulty in the parallel-electrode diode and has shown that the effect of the space charge enables the electrons to acquire additional energy from the H.T. supply, which reappears as oscillatory energy in the circuits immediately associated with the electrodes. The same action might take place with the positive-grid triode, but this possibility is ruled out by Benham's discovery that no such action could occur in a cylindrical diode without a longitudinal magnetic field. Since space charge is more accentuated in this case than in the parallel-electrode diode, this result is surprising. Moreover, it is a general experience that the triode oscillations are more easily produced at grid voltages such that thermionic saturation of the cathode has set in, and therefore when space-charge effects are less. More information on this point is very desirable. The author remarks upon the effect of the seal dividing the circuits into two parts and causing coupled-circuit effects. The seal must act very strongly as a reflector of the electrical impulses coming from the electrodes, and it may be that the difficulty experienced in getting much energy from the valves is due to the fact that a good deal of the energy generated remains inside.

With regard to the second paper, does valve No. 19 act effectively as a magnetron oscillator (i.e. for shorter waves than those for which it can be used as a dynatron oscillator), and, if so, is it as effective as the valves having directly heated filaments? Valves of the usual type, designed for amplifying and reactive oscillation, are commonly employed for the generation of centimetre waves. Has the author any evidence that these are the most suitable forms, and has he had experience of other types?

Mr. E. W. B. Gill: I disagree with the statement on page 62 in the first paper to the effect that the electron current to the anode represents a damping loss. In the first place, good oscillations can be obtained if the Lecher wires are attached, not to the grid and the anode, as is generally done, but to the anode and the filament. If the anode is only being damped, it is very difficult to see how those oscillations can possibly be maintained. My second objection is that the magnetron described by the author is virtually a 3-electrode valve with the grid removed. The electrons can be made to start, accelerate, slow down at the anode, and return, by using either a 3-electrode valve with the grid at a high potential or a magnetron. If the anode causes the damping, I do not see how oscillations can be produced at all. The author hints that as the anode is made more negative more powerful oscillations are produced. The reason for this is not that the damping is being reduced but that conditions are such that it is more difficult for the electrons to get through. In attempting to explain why electronic oscillations occur it is important

to remember that the H.T. battery can only supply the necessary energy if the potentials of the electrodes to which it is attached vary in some way. This disposes of the idea that the Barkhausen-Kurz oscillations are independent of conditions outside the valve. In my opinion there is not the slightest difference between the Barkhausen-Kurz oscillations and the Gill-Morrell oscillations. The former were supposed to take place even though there was no alteration in the potential of the electrodes and therefore no possibility of the H.T. battery supplying energy. For oscillations to occur, the continuous current normally supplied by the H.T. battery must be changed into an intermittent current. This can happen only in one of two ways: (*a*) by the space round the filament becoming saturated, or (*b*) as the result of a variation in the current coming out of the valve through the grid, owing to the anode taking intermittent current. Now it is quite true that in certain cases oscillations are obtained when the filament is not saturated. Hence the intermittency which gives the H.T. battery the possibility of supplying energy is due to the collection on the grid of current which is not uniform. In valves in which the anode is very large compared with the grid, the electrons approach the grid in a uniform stream; some of them pass through, but from time to time the relative amounts fluctuate. When the anode is not very large compared with the grid, the filament emission is affected as the result of the space round the filament becoming saturated.

Mr. W. F. Tedham: I also find it difficult to understand the mechanism whereby electronic oscillations in a triode are maintained. No doubt the space charges are an important factor in the problem. There is one space charge under the filament and another under the anode: in these space-charge regions the electrons travel slowly and therefore the electron density is higher than elsewhere. The energy of two oscillating space charges is very small, however, and quite insufficient to maintain oscillations of the magnitude obtained in the external circuit. Mr. Bull, when discussing this subject with me, suggested that the space charge around the grid wires, due to secondary emission, must play some part. I think that the phenomenon of secondary emission in valves is apt to be neglected. It is almost impossible to obtain a metal surface in a state in which it does not emit secondary electrons when bombarded with electrons over about 20 volts. With regard to the rate at which a space charge can build up, in an unsaturated triode this is quite fast enough to account for the fastest oscillation mentioned in the paper. The phenomenon of oscillation of the space charge falls into line with some oscillations observed by Dr. Langmuir in gas discharges, in which there are equal numbers of positive and negative ions. As far as I can see, however, the positive ions are not essential to the argument, as the wavelength of waves generated in this way is of the same order as that of the waves mentioned in the paper.

Mr. G. Shearing: With regard to harmonic oscillations, dealt with in the first paper, I should like to ask the author whether the fundamental wavelength, as calculated on the basis of the fundamental electronic-oscillation frequency, was observed in addition to the harmonic. If so, what were the relative amplitudes? In the course of some experimental work with the French TMC valve as used by Pierret, we have obtained wavelengths of the order of 15 to 18 cm, but we have never observed the fundamental wave to which the author refers. With regard to his opinion that the magnetron is better than the triode for electronic oscillations, is not the loss in the grid of the triode partially counterbalanced by the loss in the anode of the magnetron? Turning to Fig. 7 of the first paper, in the circuit of the micro-transmitter it is possible to replace the anode biasing battery by a suitable resistance. If this resistance is variable it can be used to obtain control (of the order of 10 per cent) of the wavelength with practically no loss of efficiency. With reference to super-regenerative reception (Fig. 8 of the first paper) our experience over short ranges has been that little gain is obtained. In this connection Carrara states in a recent paper* that super-regeneration has a very limited efficiency and may be harmful. I should like to ask whether the author has carried out much experimental work on the super-regenerative type of receiver.

Turning to the second paper, the author's method of obtaining a concentrated field and of avoiding troubles due to the inter-electrode capacitance of the anode and filament leads is probably the explanation of the excellent results obtained in comparison with those given by the split magnetron, as used by Okabe. It is stated on page 75 that electronic oscillations only occur when the electrons have no velocity component normal to the surface of the anode. In this connection, according to our experiments, the production of oscillations in the split magnetron is always accompanied by overheating of the two halves in certain well-defined spots on the two edges facing the electron stream. Can this be explained by what might be called the " grazing-action " theory? I feel that the narrow gap in the split anode is an important factor in the production of large-amplitude oscillations. Will the author explain what he means by the positive and negative tilts of the magnetic field? Has he ever observed any asymmetrical heating of the anodes when working under the conditions illustrated in Fig. 14? Diagram (*c*) suggests that such an effect might occur. Our experience shows that oscillations are only obtained when equal areas of the two halves of the split-anode system are heated similarly. With regard to the question of modulation, illustrated by Fig. 22, the conditions for obtaining a reasonable modulation without distortion are very critical. The values of the field, the mean anode voltage, and the anode-voltage variation, must all be correct for the given frequency. Any departure from the correct voltage is liable to produce harmonic distortion. In a magnetron transmission system designed to work over a band of frequencies using modulated energy it would appear better in some ways to obtain the modulation by variation of the magnetic field, at least for audio frequencies, although I am not quite sure whether trouble would not arise at the higher speech frequencies. Basing our work on the results of previous investigations carried out at the Research Laboratories of the General Electric Co., we have produced a split-anode magnetron which has

* N. CARRARA: " The Detection of Microwaves," *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 1615.

a maximum input of the order of 450 watts at 3 000 volts, working down to a wavelength of the order of 1 metre when used as a dynatron.

Dr. R. L. Smith-Rose: A great deal of the work done on this subject abroad has consisted of attempts to discriminate between two or more sets of oscillations by investigating the effects of ringing the changes on all the variables concerned. The subject may be more easily investigated by taking a somewhat simpler view of the matter and co-ordinating the various factors involved. I hope that before the subject has developed too far the question of the nomenclature may receive consideration. We are already talking of electronic oscillators, of magnetron-dynatron oscillators, and of magnetron-electronic oscillators. These terms, particularly the last two, are rather clumsy, and it is to be hoped that before their use becomes too widespread some other short but explicit terms may be found to replace them.

(*Communicated*): I should like to query the validity of distinguishing between the types of oscillators in the manner adopted by the author. May not each be regarded as a particular type of dynatron, in the sense that when it is supplied with suitable voltages, with or without a magnetic field, the valve offers a negative input impedance over a particular range of frequencies, and that if it be connected to a circuit adjusted to resonate at one of these frequencies oscillations will be generated? The feature which distinguishes it from the ordinary dynatron arrangement is that the frequencies at which the above conditions hold are restricted to certain bands. Does the author know of any instances of the generation of oscillations in a valve without the presence of a tuned circuit? Such instances would invalidate the above generalization.

Turning to the second paper, the wavelengths dealt with in Figs. 5, 6, 7, and 10, and the accompanying text, are of the order of eight times the circuit length. If this is a result of the lumped capacitance at the seal, it is difficult to understand how proportionality between the wavelength and circuit length is obtained as described on page 73. The author is perhaps not sufficiently explicit in his use of the terms "internal" and "external" circuit. There is no mention of secondary emission throughout the two papers. Has the author's experience led him to adopt the view that secondary emission plays a negligible part in the production of electronic oscillations?

Mr. W. E. Benham: The Barkhausen-Kurz conception of the mechanism of electronic oscillations has already been criticized by other speakers. As I see it, its main weakness lies in the fact that the turning-back of the electrons in the grid-anode space is determined in any case by the d.c. potentials, and that the chance of an electron missing the grid twice may be very small. In Section 3 (*a*) of the first paper the author claims to be able to predict mathematically or qualitatively the existence of a negative conductance in diodes. I differ from him in that I find mathematically that, neglecting space-charge forces, negative conductance cannot arise. The (to me) surprising result that space charge makes possible negative conductance in a plane diode is not nearly so easy to explain as the result that the dielectric constant κ is less than unity. Without attempting here any basic explanation, I would mention that the negative conductance property may be regarded as arising from the fact that the total current (including displacement current) does at certain frequencies lead the applied potential by a phase angle in excess of $\pi/2$. The incidence of negative conductance predicted by classical electronics is the keynote of the following as yet unpublished (and, frankly, somewhat crude) explanation of the mechanism of electronic oscillations. In Fig. A, which

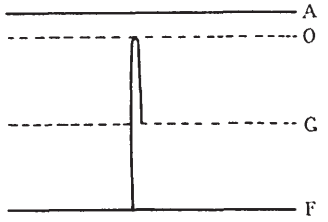

FIG. A.

is a schematic representation either of the plane- or of the cylindrical-triode case, consider only those electrons which miss the grid G on the first outward journey from the cathode F. No resultant work is done on or by electrons in the passage FO, O being at the same potential as F. Upon the transit OG alone, therefore, depends the existence of "electronic" oscillations. On mathematical grounds this transit may be responsible for negative conductance. The surface O may be regarded as the seat of a "virtual cathode."* We therefore have to regard electronic oscillations as arising in consequence of the transit of electrons from the external virtual-cathode surface O to the grid G, the degree of space-charge limitation being governed by the geometry and by the temperature of F, the ultimate source of electrons in the grid-anode space. The existence in practice of a small anode current indicates that the oscillations always build to a value sufficient to bring the anode potential from some negative value to zero (or positive) potential for a small fraction of the cycle. Immediately the anode becomes positive, however, the virtual cathode disappears and we are left for an instant without a source of energy. The anode potential therefore returns at once to its negative value, the virtual cathode is again formed, and the cycle of events is repeated.

Mr. J. S. McPetrie (*communicated*): On page 62 in the first paper the author suggests that the two values of anode bias at which maximum electronic oscillation amplitude are obtained represent the conditions for saturated and completely unsaturated space-charge in the grid-anode space. This appears surprising, as the anode bias under the two conditions was changed only from 1·5 to 9 volts.

On page 75 in the second paper the author states that the electrons which reach the anode when $2\pi/\omega = 2T$ are those which left the cathode during the positive half-cycle of the oscillations. Gill and Morell have shown that this is not quite accurate. The electrons which reach the anode are those on which positive work is done by the oscillations, and this occurs when $2\pi/\omega = 2T$, not for values of ωt between 0° and 180°, as suggested.

* L. TONKS: *Physical Review*, 1927, vol. 29, p. 913.

by the author, but for values between 300° and 120°. On the same page the author endeavours to explain the action taking place in the split-anode magnetron and states that the interval between successive current-pulses is half that in the full cylindrical-electrode magnetron. Does this mean that the frequency of the oscillations obtained with the split-anode magnetron should be twice that of the corresponding full cylindrical-anode magnetron? The author states that for the condition of maximum oscillation the emission current is proportional to the $\frac{3}{2}$ power of the anode voltage. The results given in Fig. 5 do not agree with this, as the ratio of $E_a^{3/2}/I_e$ varies between the approximate values of 22 and 7. Incidentally, it would be interesting if the author would describe how he determined the value of the emission current. At the top of page 81 in the second paper he states that the anode current decreases when the amplitude of the oscillations is large. This seems inconsistent with the results given graphically in Fig. 15. Kilgore* finds that the angle of tilt of the magnetic field is not due to the voltage-drop along the filament, and I am pleased to see that the author has altered his hypothesis so as to agree with Kilgore.

Mr. E. C. S. Megaw (*in reply*): Prof. Fortescue refers to the mechanism by which negative resistance is produced in the triode electronic oscillator, and points out the difficulties of a general explanation in terms of electron delay. The explanation suggested by Möller and others, who have extended the original theory of Barkhausen and Kurz, is briefly as follows†:—In the presence of alternating electrode potentials some of the electrons absorb energy from the external circuit and obtain extra acceleration, while others give up some of their energy with a consequent loss of acceleration. This depends on the point in the cycle at which the electrons leave the cathode. The amplitude of the first group increases, so that those electrons which pass through the grid reach the anode on their first outward journey and give up their extra energy to it, provided the anode potential is close to that of the cathode. The amplitude of the second group decreases, so that they miss the anode and continue to vibrate about the grid until they are absorbed by it. If the mean energy given up by the electrons of this group before reaching the grid is greater than the energy absorbed by the first group, negative resistance occurs.

Mr. Benham criticizes the Barkhausen–Kurz hypothesis chiefly on the grounds that "the chance of an electron missing the grid twice may be very small." Experimental results do not support this contention. In particular, for a typical triode it has been found that the maximum (space-charge-limited) current to the grid with the anode at cathode potential is some 35 per cent less than the maximum current to grid and anode when both are at the same potential. This indicates that a considerable number of electrons must have passed through the grid at least twice so as to increase the space-charge density between grid and cathode. Further, with the grid and anode at the same potential, about 75 per cent of the total space current passed through the grid. While this figure will be somewhat reduced by the extra space-charge between grid and anode and round the grid wires when the anode is at cathode potential, the experimental results strongly suggest the possibility of electrons passing through the grid wires several times before being absorbed.

In reply to the other points raised by Prof. Fortescue, magnetrons with indirectly heated cathodes generate electronic oscillations at least as easily as those with filament cathodes. With regard to the best electrode form for triode electronic oscillators, the results obtained by various workers with special electrode forms (e.g. flat plate, parallel wire, external cylindrical cathode) suggest that these are not superior to the ordinary cylindrical construction.

In reply to Mr. Gill, the fundamental reason for considering that the electron current to the anode of a triode electronic oscillator represents a damping loss is that those electrons which reach the anode have obtained the extra energy enabling them to do so from the oscillatory circuit. This energy reappears as heat at the anode. I am glad to note that Mr. Gill agrees with the opinion expressed in the first paper that the so-called "B-K" and "G-M" oscillations are identical. His suggestion that there are two possible mechanisms of excitation (one operating when the anode diameter is very large and the other when it is not very large, compared with the grid diameter) is essentially the same as the suggestion made at the end of Section 2 (*b*) of the first paper (page 60). The experimental results for the former case are, however, still rather limited and the possibility of a common explanation for both cases should not be ignored.

Mr. Tedham and Dr. Smith-Rose mention the possibility that secondary emission may be of importance in the mechanism of electronic oscillations. While this possibility has not been overlooked, the experimental results have not so far suggested its importance. In the triode, grid secondary emission will increase the space-charge round the grid wires to some extent, since the velocities of most of the secondary electrons are much lower than those of the primary electrons. It seems probable that the only important result will be to increase the effective closeness of the grid mesh. In the triode electronic oscillator the final velocity of electrons reaching the anode is small and anode secondary emission is not likely to be important. In the magnetron case, anode secondary emission will increase to some extent the already large space charge in the immediate neighbourhood of the anode.

Mr. Tedham's suggestion that positive ions are not essential to the mechanism of electronic oscillations is confirmed by the recent experimental results of Rindfleisch.*

In answering Mr. Shearing's question about harmonic oscillations it is necessary to distinguish between the harmonics of an electronic oscillation resulting from non-sinusoidal wave-form and the "overtone" or "dwarf-wave" oscillations obtainable with fixed valve voltages and varying circuit dimensions. The former have been detected by Tank and others, simultaneously with the fundamental, but their amplitude is generally very small. The "overtone" oscillations exist independently of the fundamental. The fundamental

* *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 1741.
† See also H. Edler: *Archiv für Elektrotechnik*, 1932, vol. 26, p. 841.

* *Annalen der Physik*, 1932, vol. 14, p. 273.

oscillations have been observed in TMC valves with a circuit of suitable dimensions connected between grid and anode. My experience of the use of super-regeneration in electronic oscillation receivers has not been extensive, but I would agree with Mr. Shearing that little gain is obtained with strong signals. With weak signals, however, a useful gain has been observed. It appears that there may be some confusion between electronic and dynatron oscillations in Mr. Shearing's question about magnetron anode heating. Provided the filament is accurately centred, the tendency for electronic oscillations to produce uneven heating is small. The idea of " grazing incidence " is not involved in the conception of the dynatron oscillations; and the maximum heating has always been observed on the " trailing," and not the " leading " edges of the anode segments (see Fig. 3, page 79). I understand that Mr. Shearing's more recent observations are in agreement with this. The sign of the angle of tilt of the magnetic field is defined by the conventions that the " sense " of a magnetic field is north to south, and that the positive direction along the filament is from the positive to the negative pole. With regard to magnetron modulation, for dynatron oscillations the ideal condition appears to be simultaneous variation of anode voltage and magnetic field strength, but, as Mr. Shearing points out, field-strength variation involves difficulties in design for the higher audio frequencies.

The distinction made between the " electronic " and " dynatron " oscillations generated by magnetron valves is based on the fact that the production of the former depends critically on the time of transit of the electrons, while the production of the latter only requires the transit time to be short compared with the oscillation period. If this distinction were ignored, for the reasons given by Dr. Smith-Rose, it would appear logically necessary to include reaction oscillations in the same category. So far as I am aware, the production of oscillations in a hard valve always requires the existence of a tuned circuit of some description. The nomenclature of the subject is admittedly rather clumsy in some cases, but the system adopted was considered preferable to using the names of the discoverers. As possible alternatives to " electronic," " magnetron-electronic," and " magnetron-dynatron " oscillations respectively, the terms " inertia," " magneto-inertia," and " magneto-deflection " oscillations may be suggested. Regarding the resonant wavelength of a parallel-wire system of length l terminated at one end by a short-circuit and at the other by a small capacitance, this approaches the value $4l$ as l increases. When l is small the wavelength is greater than $4l$.

On further consideration I must agree with Mr. Benham that the existence of negative conductance in a diode does apparently involve the space-charge forces. My only objection to his explanation of triode electronic oscillations on the basis of his analysis of the diode case is that the oscillation wavelength calculated on this basis is much smaller than the wavelength observed in typical cases, including that of the flat-electrode triode described by Wundt.*

In reply to Mr. McPetrie, the reason for supposing that a change of anode bias from 1·5 to 9 volts might increase the space-charge between grid and anode by a considerable amount is that with an oscillation amplitude of a few volts many of the electrons which reach the anode on their first outward journey at the lower bias voltage would return towards the grid at the higher value. The paper does not imply that the space-charge density is negligible in the first case, but simply that it is below the saturation value. It was not intended to suggest that the frequency of a split-anode magnetron oscillator should be twice that of the full cylindrical-anode oscillator, but that current pulses were received successively by the two halves of the circuit. While it is true that the lower part of the curve of optimum emission current (measured without magnetic field) in Fig. 5 departs from the $\frac{3}{2}$ power law, this law has been found to fit approximately to observations on several valves. Referring to Fig. 15, no oscillations were observed when the anode current exceeded 20 mA. The increase in current beyond the point P may have been due to the presence of residual gas.

* *Zeitschrift für Hochfrequenztechnik*, 1930, vol. 36, p. 133.